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Short Communication

Optimization of biomass torrefaction conditions by the Gain and Loss method and regression model analysis

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HIGHLIGHTS

- The optimal conditions for biomass torrefaction were determined by Gain and Loss method.
- The models chosen by regression analysis were different depending on biomass.
- The optimized severity factors on each biomass ranged from 6.056 to 6.372.
- The optimized temperature was 248.55 °C when torrefaction was performed for 60 min.

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ABSTRACT

In this study, the optimal conditions for biomass torrefaction were determined by comparing the gain of energy content to the weight loss of biomass from the final products. Torrefaction experiments were performed at temperatures ranging from 220 to 280 °C using 20–80 min reaction times. Polynomial regression models ranging from the 1st to the 3rd order were used to determine a relationship between the severity factor (SF) and calorific value or weight loss. The intersection of two regression models for calorific value and weight loss was determined and assumed to be the optimized SF. The optimized SFs on each biomass ranged from 6.056 to 6.372. Optimized torrefaction conditions were determined at various reaction times of 15, 30, and 60 min. The average optimized temperature was 248.55 °C in the studied biomass when torrefaction was performed for 60 min.

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1. Introduction

Among fossil fuels used today, coal remains the most commonly employed in power generation. Worldwide coal consumption was 3724 MT in 2011 (BP Energy Report, 2012). As coal continues to maintain its popularity, lawmakers are continuing to enforce stricter laws on green house gas emissions. One possible way to reduce the consumption of coal by the power generation industry is to mix biomass with coal.

Compared to fossil coal, biomass still has several drawbacks as a renewable energy source due to its chemical compositions. Carbon and oxygen content in biomass are around 50% and 30%, respectively; its calorific value is about 59% that of conventional fossil fuels (Swithenbank et al., 2011). Along with its poor fuel characteristics, the significant bulk of biomass is problematic in terms of transportation and storage. Furthermore, the fibrous characteristics of biomass cause difficulties in grinding when adding it to feed hoppers for furnaces. Wood pellets or wood chips have been considered as candidates in co-firing with coal (Bergman et al., 2005). However, different type of grinding machines and other infrastructure, including storage facilities, are required due to differences physical and chemical characteristics between wood pellets and coal.

In order to overcome these problems, torrefaction by thermal treatment has been proposed. This process is generally defined to be a mild thermal treatment of a target biomass in temperatures ranging from 200 to 300 °C in the absence of oxygen with the inclusion of an inert carrier gas at atmospheric pressure. This process generally produces a mass with 10% of energy loss and 30% of its weight loss (Bergman et al., 2005). Over the past several years, numerous studies have been performed on the effects of non-oxidizing torrefaction conditions on the physical and chemical properties of biomass, such as weight loss, elemental variation, grindability, calorific value, energy yield, and thermal degradation kinetics of biomass(Chen and Kuo, 2011; Medic et al., 2012).

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Optimization studies to elucidate the kinetic mechanism of torrefaction have been performed using the response surface analysis method (Kim et al., 2013; Lee et al., 2012; Na et al., 2013a,b). However, the optimum conditions for torrefaction at a production level were not determined above studies. A conventional method of comparison for torrefaction conditions is to examine the energy yield of the product. The energy yield is normally defined as the ratio of the increase of calorific value to the decrease of biomass weight. In order to achieve the higher energy yield through torrefaction, the increase in calorific value should be greater than the loss of weight. However, the energy yield of torrefied biomass is eventually reduced compared to the energy content of raw material, and the diverse variations in moisture content, ratios of chemical compositions depending on biomass also make this ambiguous.

Optimizing the torrefaction process could improve both the quantity and quality of torrefied biomass demanded by consumers. Therefore, maximizing the calorific value and minimizing the weight loss from raw material is conceived as the optimized torrefaction condition. In this study, we focused on finding the optimization conditions of torrefaction based on minimizing the weight loss and maximizing the calorific gain.

2. Methods

2.1. Sample preparation

Seven types of biomass were used in this study, which are Eucalyptus, Larch, Yellow poplar, Acacia, Albasia, Mixed softwood, and Mesocarp as oil palm residues. Before torrefaction, wood chips, except Mesocarp, were screened to the size of 10–30 mm, using sieves (9.5 and 31.5 mesh) and dried at 105 °C for 24 h to below 10% moisture content for safe outside storage.

2.2. Experimental design and torrefaction process

Each biomass was torrefied according to the 2^2 factorial experimental design (Lee et al., 2012). The temperature (220–280 °C) and reaction time (20–80 min) were considered as factors for experimental design. The severity factor (SF) was used to integrate the effects of those into a single variable (Lloyd and Wyman, 2005). The torrefaction reactor used in all experiments was a batch reactor equipped with a temperature controller, designed by Drying Engineering Inc. Korea.

2.3. Elemental analysis and calorific value

The moisture content of torrefied biomass was determined using the oven-dry method. The gross calorific value based on the dry weight at constant volume was determined by a Parr 6400 automated isoperibol bomb calorimeter. A ash content was determined by burning the oven-dried sample (1 g) in a platinum crucible in a muffle furnace model at 575 ± 25 °C. The nitrogen, carbon, and hydrogen content of the torrefied biomass were assessed via direct combustion. Thermal conductivity was detected by using an elemental analyzer (Thermo EA1112A, USA).

2.4. Application of Gain and Loss method and the regression model

The concept of Gain and Loss was developed to find the optimized condition of torrefaction for each biomass. Energy yield is the ratio of the increase in calorific value to the decrease of weight. The energy yield is highest when the difference between the weight loss and calorific value is large. However, it is not the optimized condition and the quantitative projection in terms of yield.

The basic concept behind the Gain and Loss method is that the torrefaction conditions of raw biomass are optimized at the intersection of the regression curves of calorific value and biomass weight versus SF. We defined the optimized condition at this intersect point, where the gain in calorific value and loss of weight are in state of trade-off. This definition of the optimum conditions for torrefaction, along with the application of the Gain and Loss method, has the potential to overcome the ambiguity inherent in attempting to optimize the energy yield. We considered the possibility that the order of the regression model might be different depending on biomass. Three polynomial regression models were compared, ranging from 1st to 3rd order. Because of differences between unit and value in terms of calorific value (MJ/kg) and weight loss as a percentage (wt.%), it is necessary to normalize the two types of data to the same unit, as given in Eq. (1). Each value was divided by the root–mean–square of column. All data transformed by this function was set up from 0 to 1 depending on the each value (*x* is severity factor).

$$\text{Normalized value} = \frac{x_i}{\sqrt{\sum_{i=1}^{i=n} x_i^2/(n(i)-1)}} \qquad (1)$$

2.5. Statistical analysis

The statistical program used was statistical language 'R'. Polynomial regression analysis was applied using equations ranging from 1st to 3rd order. ANOVA was performed to verify the significance of the regressions at the 95% confidence level. If no significant difference was determined, 1st order regression was applied for further analysis. Graphs were drawn using the 'ggplot2' packages in 'R'.

3. Results and discussion

3.1. Changes in carbon content and H/C ratio

Torrefaction induced a significant increase of carbon ratio in biomass. The carbon content of raw material was Mixed softwood (54.47%), Larch (52.30%), Mesocarp (52.11%), Acacia (50.82%), Eucalyptus (49.88%), Albasia (49.37%), and Yellow poplar (47.81%). The carbon content of the product increased with increasing of SF. The highest increase was 5.87% (in Yellow poplar), while the minimum increase was 3.99% (in Albasia). Carbon content is directly connected to the energy density in terms of calorific value, therefore, the increase of carbon content in a given unit mass of fuel implies the improvement of fuel energy (Chin et al., 2013b; Medic, 2012).

Hydrogen content was slightly decreased or not changed in percentage ratio by torrefaction. The hydrogen content was reduced by 0.59% in Mesocarp compared to that of raw material. In the cases of Yellow poplar and Albasia, the hydrogen content was increased by 0.01% and 0.147%, respectively. The relationship between H/C ratio and SF could provide more clues for describing the effect of torrefaction (Fig. 1). The H/C ratio of Mesocarp steeply decreased with increasing SF. We explain this by noting that Mesocarp contains much more hemicellulose as compared to that of other studied biomass (Uemura et al., 2011). The hemicellulose content in biomass is confirmed as an important factor for torrefaction (Bergman et al., 2005; Chin et al., 2013b).

3.2. Gain of calorific value, weight loss and energy yield

Calorific value increased with torrefaction severity regardless of the biomass used. Reaction times from 20 to 80 min were studied, and we presumed that these are sufficient reaction times to

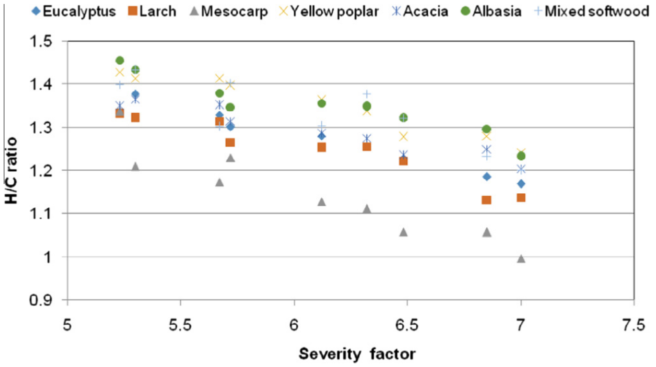

Fig. 1. The change of H/C ratio of torrefied biomass dependent on severity factor (SF).

complete the torrefaction process. As discussed in Section 3.1, the change in carbon content depending on torrefaction conditions was highly correlated to the calorific value.

The change in calorific value and weight loss are shown in Supplementary data (Table S1). Under SF 7, most of biomass tested lost more than 23% of their starting weight (Min. 23.48% in Eucalyptus, Max. 39.22% in Mesocarp). The calorific value increase ranged from 7% to 19.2% (Min. 7% in Eucalyptus, Max. 19.2% in Mesocarp). The variations in the torrefaction efficacy can be attributed to the differences in the composition of various types of biomass. The variations in weight loss are larger than that of calorific gain in terms of percentage.

The energy yield was continuously reduced through torrefaction under all SFs even though the reduction rates are different depending on biomass (Supplementary data, Fig. S1). Compared to raw materials, the loss of energy yield ranged from 20% to 30% (dry basis) dependent on biomass. In Mesocarp, energy yield significantly decreased compared to others. This result implies that the net usable energy of raw material has decreased (Bergman et al., 2005; Chin et al., 2013a; Medic, 2012). The determination of the energy yield is insufficient to appropriately optimize the conditions for torrefaction.

A general method to optimize torrefaction conditions for biomass has yet to be determined (Chin et al., 2013b). One purpose of torrefaction is to increase the energy density of a target material. The energy density of torrefied biomass is increased after reaction, but the total energy decreases due to weight loss. Ideally, optimized torrefaction conditions would produce a balance between the quality and quantity of products, making it a process potentially useful from an industrial point of view.

3.3. Regression models of calorific value and weight loss

Changes in calorific value and weight loss were determined, and the correlation with SF was assessed. All regression models were tested through ANOVA analysis whether models are statistically significant or not at 95% of a significant level. The models chosen by this regression analysis were different depending on biomass (Table 1). In the case of Eucalyptus, 1st order regression was chosen. For Larch, Acacia, and Albasia, 2nd order polynomials were chosen. Change in calorific value was determined by 2nd order regression for Mesocarp. Finally, the 3rd order formulae were used for mixed softwood. The optimized severity factors for torrefaction were 6.372 (Mixed softwood), 6.209 (Larch), 6.142 (Albasia), 6.130 (Acacia), 6.099 (Mesocarp), 6.057 (Eucalyptus) and 6.056 (Yellow poplar) in order. We find that optimum conditions for torrefaction seem to fall within a narrow. The SF selected for the optimization of torrefaction conditions of raw biomass was the intersection of the regression curves of increase of calorific value and the decrease of weight. It was assumed that this intersect point was where the gain in energy and loss of weight are in a state of trade-off.

The optimization condition of torrefaction ranged from SF 6.056 to 6.372 regardless of the biomass used (Fig. 2). R-square values were calculated from 0.876 (Albasia) to 0.979 (Larch, Acacia and Mixed softwood). Even though the range of optimized SFs was narrow, the differences in the selected regression models indicate that the effects of torrefaction on biomass are dominated by various characteristics inherent to the biomass used.

3.4. The gain of calorific value and the weight loss under optimized SF

Under the optimized SFs obtained from the regression analysis of each biomass, the gain of calorific value and weight loss through torrefaction were assessed as shown in Fig. 3. The gain of calorific value was expected to range from 4% to 12% compared to that of raw material, with the highest gains to be found in Larch. The average calorific value of biomass was estimated to be 20.60 MJ/kg by torrefaction under this optimized reaction condition. The highest weight loss was in Mesocarp (24%), while the lowest was obtained from Acacia (10%). The energy density increased from 117% to 141% dependent on the type of biomass used. Change in energy density was the largest in Mesocarp (141%), while Albasia had the smallest (117%). The difference in energy density is a result of the structures and content of hemicellulose in deciduous and coniferous wood. Deciduous wood in particular is much more reactive and results in significantly more devolatilization (Bergman et al., 2005).

Table 1
The selected severity factors (SF) and *R*-square as determined by regression model.

Raw material	Type	Regression formula	Order	*R*-square	*p*-Value	SF	*Y* value
Eucalyptus	Calorific value	$CV = 0.0289 \ast (SF) + 0.7670$	1st	0.946	6.92E−06	6.057	0.942
	Weight loss	$WL = -0.1351 \ast (SF) + 1.7603$	1st	0.967	1.21E−06		
Larch	Calorific value	$CV = 0.0699 \ast (SF) + 0.5168$	1st	0.924	2.27E−05	6.209	0.951
	Weight loss	$WL = -0.0802 \ast (SF)^2 + 0.8591 \ast (SF) - 1.2914$	2nd	0.979	3.88E−06		
Yellow poplar	Calorific value	$CV = 0.0685 \ast (SF) + 0.5256$	1st	0.921	2.63E−05	6.056	0.940
	Weight loss	$WL = -0.1652 \ast (SF) + 1.9410$	1st	0.964	1.69E−06		
Mesocarp	Calorific value	$CV = 0.0400 \ast (SF)^2 - 0.4272 \ast (SF) + 2.0478$	2nd	0.896	0.0004	6.099	0.930
	Weight loss	$WL = -0.1979 \ast (SF) + 2.1373$	1st	0.939	1.07E−05		
Acacia	Calorific value	$CV = 0.0387 \ast (SF) + 0.7071$	1st	0.946	1.16E−06	6.130	0.944
	Weight loss	$WL = -0.0366 \ast (SF)^2 + 0.3173 \ast (SF) + 0.3747$	2nd	0.979	4.19E−06		
Albasia	Calorific value	$CV = 0.0408 \ast (SF) + 0.6943$	1st	0.876	0.0001299	6.142	0.945
	Weight loss	$WL = -0.0367 \ast (SF)^2 + 0.3186 \ast (SF) + 0.3726$	2nd	0.956	3.63E−05		
Mixed softwood	Calorific value	$CV = 0.0645 \ast (SF)^3 - 1.1469 \ast (SF)^2 + 6.8079 \ast (SF) - 12.5674$	3rd	0.952	0.0003176	6.372	0.933
	Weight loss	$WL = -0.1196 \ast (SF)^3 + 2.0928 \ast (SF)^2 - 12.2647 \ast (SF) + 25.0538$	3rd	0.978	4.41E−05		

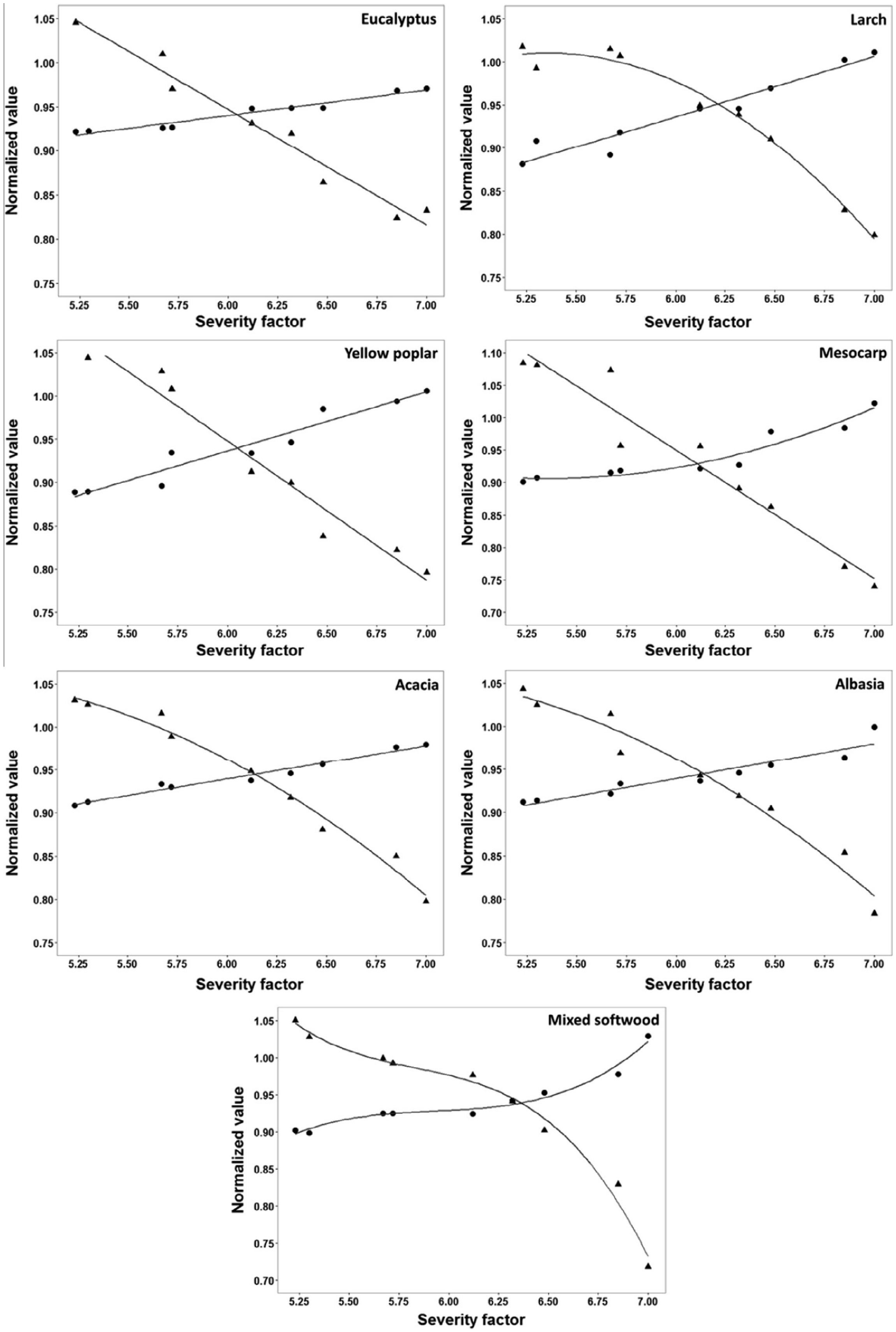

Fig. 2. The regression model of normalized calorific value and weight during torrefaction reaction (▲: the weight loss, ●: the gain of calorific value).

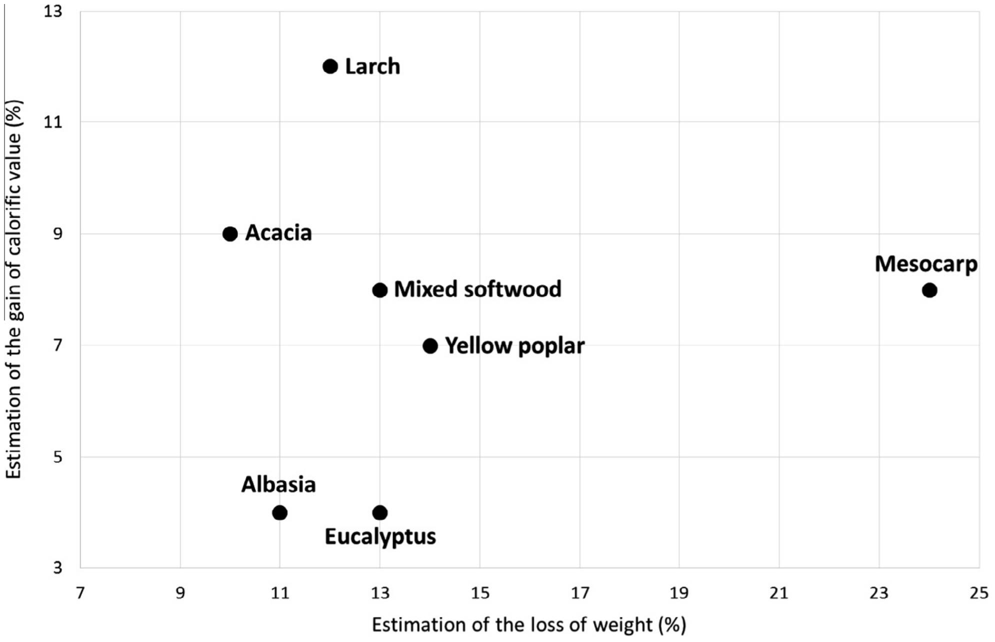

Fig. 3. The relationship between the gain of calorific value and weight loss using optimized severity factor.

Table 2
The optimization of reaction temperature and time for the chosen severity factors (SF).

Sample	Optimized SF	Scenario 1 (reaction time = 15 min)	Scenario 2 (reaction time = 30 min)	Scenario 3 (reaction time = 60 min)
		Optimized temperature estimated on the basis of Eq. (2) (°C)		
Eucalyptus	6.06	265.77	255.55	245.32
Larch	6.21	270.93	260.71	250.49
Yellow poplar	6.06	265.74	255.51	245.29
Mesocarp	6.10	267.20	256.97	246.75
Acacia	6.13	268.25	258.03	247.80
Albasia	6.14	268.66	258.43	248.21
Mixed softwood	6.37	276.47	266.25	256.02
Average		269.00	258.78	248.55
Standard deviation		3.75	3.76	3.75
Variation		14.08	14.10	14.09

Larch displayed the higher calorific gain and the lower weight loss among the studied biomass. The weight loss of Eucalyptus was similar to mixed softwood and Yellow poplar, however, the calorific gain is lowest among the biomass sources we studied. This result implies that Larch might be preferred by producers because the quality and product yield are expected to be better than Eucalyptus. In addition, Acacia might be preferred over Albasia because although they display similar weight loss (about 10%), Acacia displays higher calorific gain (about 9%).

3.5. The optimization of torrefaction conditions by SF

The optimization of torrefaction conditions is dependent on the type of biomass used, making it similar to any other process applied to biofuels. As discussed in several other papers (Bergman et al., 2005; Chin et al., 2013b; Luo, 2011; Medic, 2012; Shang et al., 2012), physical properties of biomass starting materials, such as particle size distribution and density also influence on the torrefaction process. The optimized temperature and reaction time were estimated by the reversed transformation of Eq. (2) (Table 2). We find that the average temperature of optimized torrefaction in the studied biomass types was 248.55 °C when torrefaction was performed for 60 min. The highest temperature needed was for mixed softwood at 256.02 °C, while relatively low temperature is used for Yellow poplar and Eucalyptus at 245.29 °C. The average temperature of optimization increased from 248.55 to 269 °C as the reaction time decreased from 60 min to 15 min. The optimized temperature increased about 10 °C when the reaction time is reduced to half. We conclude from these findings that the optimal conditions for torrefaction are more reliant on the temperature than the reaction time. This finding is consistent with the isothermal decomposition models of biomass previously discussed (Chen and Kuo, 2011).

$$SF = \log\{t.\exp[(T_H - T_R)/14.75]\} \qquad (2)$$

4. Conclusion

Torrefaction of 7 types of biomass were performed in order to study the optimization of torrefaction conditions. Calorific value increased with torrefaction severity regardless of the biomass used. However, the energy yield and weight loss were continuously reduced through torrefaction under all SFs. Optimal conditions for torrefaction were determined on the basis of the concept of the gain of calorific value and the weight loss by polynomial regression analysis. The average optimal temperature was 248.55 °C for 60 min torrefaction. Based on these results, further studies are required to understand the underlying factors leading to the effect of thermal decomposition of biomass. The relationship between the method provided in the report and the quality of torrefied biomass needs to be explained more completely in the near future.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.biortech.2014.09.016.

References

Bergman, P.C.A., Boersma, A.R., Zwart, R.W.R., Kiel, J.H.A., 2005. Torrefaction for biomass co-firing in existing coal-fired power stations. ECN Biomass, 1–71.

British Petroleum. 2012. BP Statistical Review of World Energy June 2012.

Chen, W.H., Kuo, P.C., 2011. Isothermal torrefaction kinetics of hemicellulose, cellulose, lignin and xylan using thermogravimetric analysis. Energy 36, 6451–6460.

Chin, K.L., H'ng, P.S., Go, W.Z., Wong, W.Z., Lim, T.W., Maminski, M., Paridah, M.T., 2013a. Optimization of torrefaction conditions for high energy density solid biofuel from oil palm biomass and fast growing species available in Malaysia. Ind. Crop. Prod. 49, 768–774.

Chin, K.L., H'ng, P.S., Go, W.Z., Wong, W.Z., Lim, T.W., Maminski, M., Paridah, M.T., Luqman, A.C., 2013b. Optimization of torrefaction conditions for high energy density solid biofuel from oil palm biomass and fast growing species available in Malaysia. Ind. Crop. Prod. 49, 768–774.

Kim, Y.H., Na, B.I., Lee, S.M., Lee, H.W., Lee, J.W., 2013. Optimal condition for torrefaction of eucalyptus by response surface methodology. J. Korean Wood Sci. Technol. 41, 497–506.

Lee, J.W., Kim, Y.H., Lee, S.M., Lee, H.W., 2012. Optimizing the torrefaction of mixed softwood by response surface methodology for biomass upgrading to high energy density. Bioresour. Technol. 116, 471–476.

Lloyd, T.A., Wyman, C.E., 2005. Combined sugar yields for dilute sulfuric acid pretreatment of corn stover followed by enzymatic hydrolysis of the remaining solids. Bioresour. Technol. 96, 1967–1977.

Luo, X., 2011. Torrefaction of biomass – a comparative and kinetic study of thermal decomposition for Norway spruce stump, poplar and fuel tree chips. Swedish University of Agricultural Sciences, Uppsala, pp. 82.

Medic, D., 2012. Investigation of torrefaction process parameters and characterization of torrefied biom. In: Department of Agricultural Engineering; Biorenewable Resources and Technology, Vol. (Doctor of Philosophy), Iowa State University. Ames, Iowa.

Medic, D., Darr, M., Shah, A., Potter, B., Zimmerman, J., 2012. Effects of torrefaction process parameters on biomass feedstock upgrading. Fuel 91, 147–154.

Na, B.I., Ahn, B.J., Cho, S.T., Lee, J.W., 2013a. Optimal condition of torrefaction for the high-density solid fuel of larch (*Larix kaempferi*). Korean Chem. Eng. Res. 51, 739–744.

Na, B.I., Kim, Y.H., Lim, W.S., Lee, S.M., Lee, H.W., Lee, J.W., 2013b. Torrefaction of oil palm mesocarp fiber and their effect on pelletizing. Biomass Bioenergy 52, 159–165.

Shang, L., Nielsen, N.P.K., Dahl, J., Stelte, W., Ahrenfeldt, J., Holm, J.K., Thomsen, T., Henriksen, U.B., 2012. Quality effects caused by torrefaction of pellets made from Scots pine. Fuel Process. Technol. 101, 23–28.

Swithenbank, J., Chen, Q., Zhang, X., Sharifi, V., Pourkashanian, M., 2011. Wood would burn. Biomass Bioenergy 35, 999–1007.

Uemura, Y., Omar, W.N., Tsutsui, T., Yusup, S.B., 2011. Torrefaction of oil palm wastes. Fuel 90, 2585–2591.